Neutrinos: A History

Solar Neutrinos

Atmospheric Neutrinos

Neutrino Mixing

Cosmic Neutrinos

Current Experiments

Future Experiments

ν Applications

Conclusions

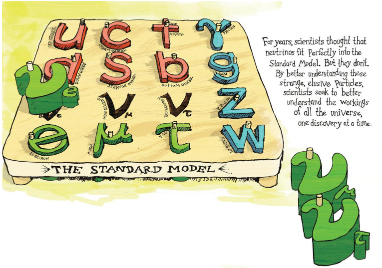
The Little Neutral One

A brief introduction to neutrinos
African School for Fundamental Physics and its Applications (ASP 2016), Aug 1-9, Kigali, Rwanda

Mary Bishai
Brookhaven National Laboratory

August 15, 2016

About Neutrinos



From Symmetry Magazine, Feb 2013

Cosmic Gall
by John Updike

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.

A BRIEF HISTORY OF THE NEUTRINO

Neutrino Conception

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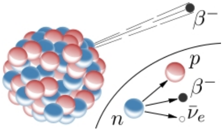
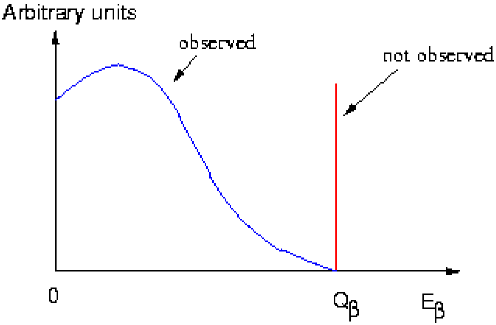


Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



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Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen:

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

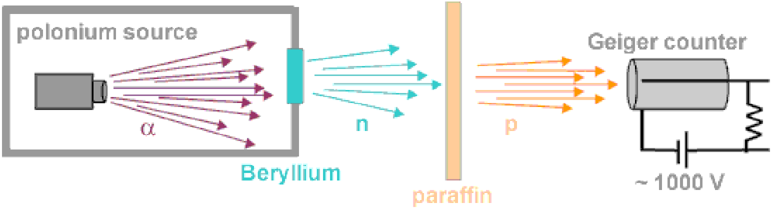
.........., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant..........
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant

. W. Pauli

Neutrino Conception

1932: James Chadwick discovers the neutron, $mass_{neutron} = 1.0014 \times mass_{proton}$ - its too heavy - cant be Pauli's particle

James Chadwick



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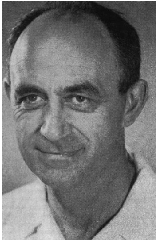
Solvay Conference, Bruxelles 1933: Enrico Fermi proposes to name Pauli's particle the "neutrino".

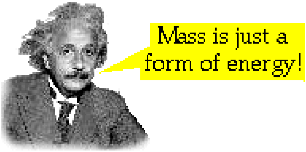


Enrico Fermi

Particle physics units and symbols

Symbols used for some common particles:

Symbol	Particle
ν	Neutrino
γ	Photon
e^-	Electron
e^+	Anti-electron (positron)
p	proton
n	neutron
N	nucleon - proton or neutron



Particle physicists express masses in terms of energy, $E = mc^2$
Mass of proton $= 1.67 \times 10^{-24}$ g $\approx$ 1 billion (Giga) electron-volts (GeV)
1 thousand GeV = energy of a flying mosquito

Finding Neutrinos...

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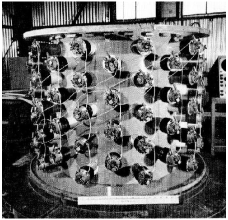
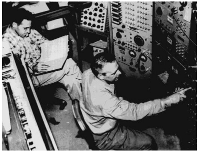
1950's: Fred Reines at Los Alamos and Clyde Cowan use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.

The detection sequence was as follows:

1. $\bar{\nu}_e + p \to n + e^+$
2. $e^+ + e^- \to \gamma\gamma$
3. $n +^{108} Cd \to^{109} Cd* \to^{109} Cd + \gamma$ $(\tau = 5\mu s)$.





Neutrinos first detected using a nuclear reactor!

Reines shared 1995 Nobel for work on neutrino physics.

ν: A Truly Elusive Particle!

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Reines and Cowan were the first to estimate the interaction strength of neutrinos.

The cross-section is $\sigma \sim 10^{-43}\mathrm{cm}^2$ per nucleon (p,n).

$$\nu \text{ mean free path} = \frac{\text{Mass of the proton}}{\sigma \times \text{density}}$$

$$\begin{aligned}
&= \frac{1.67 \times 10^{-24} g}{10^{-43} cm^2 \times 11.4 g/cm^3} \\
&\approx 1.5 \times 10^{16} m \\
&= \text{1.6 LIGHT YEARS OF LEAD} \\
&= 100,000 \text{ distance earth to sun}
\end{aligned}$$

A proton has a mean free path of 10cm in lead

Neutrino detectors have to be MASSIVE

Discovery of the Muon (μ)

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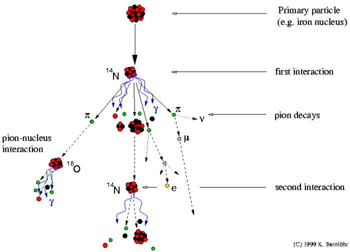
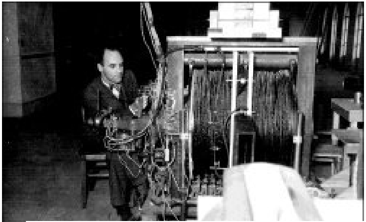
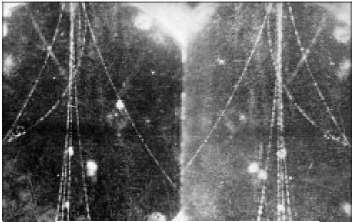
1936: Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).

Development of cosmic-ray air showers





C. Anderson with a magnetized cloud chamber



Cosmic tracks in a cloud chamber

The Lepton Family and Flavors

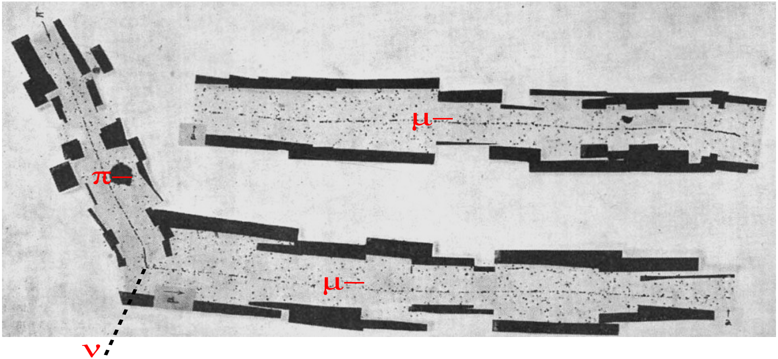
The muon and the electron are *different "flavors" of the same family of elementary particles called leptons*.

Generation	**I**	**II**	**III**
Lepton	e^-	μ	τ
Mass (GeV)	**0.000511**	**0.1057**	**1.78**
Lifetime (sec)	**stable**	2.2×10^{-6}	2.9×10^{-13}

Neutrinos are neutral leptons. **Do ν's have flavor too?**

Discovery of the Pion: 1947

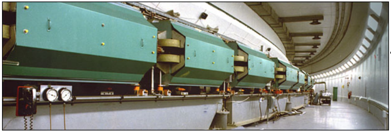
Cecil Powell takes emulsion photos aboard high altitude RAF flights. A charged particle is found decaying to a muon:



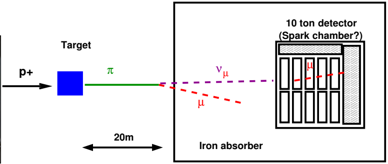
mass$_{\pi^-}$ = 0.1396 GeV/c^2 , τ = 26 nano-second (ns).
Pions are composite particles from the "hadron" family which includes protons and neutrons.

Producing Neutrinos from an Accelerator

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use a proton beam from BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \rightarrow \mu\nu_x$



The AGS



Making ν's

The Two-Neutrino Experiment

Result: **40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$**

The first successful accelerator neutrino experiment was at Brookhaven Lab.

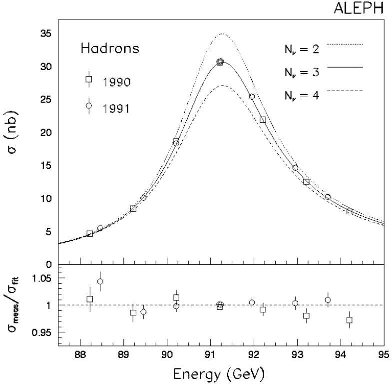
1988 NOBEL PRIZE

Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.

The LEP e^+e^- collider at CERN, Switzerland

The 27km LEP ring was reused to build the Large Hadron Collider



$$N_\nu = 2.984 \pm 0.008$$

The Particle Zoo

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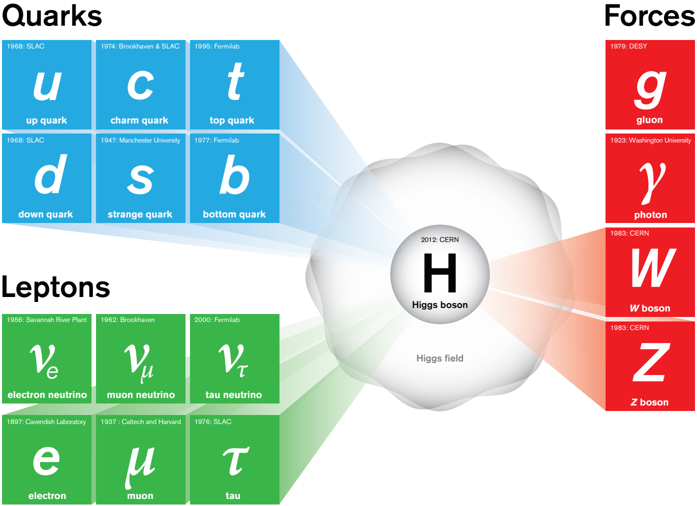
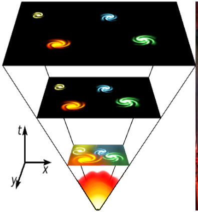
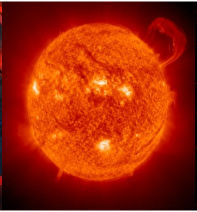
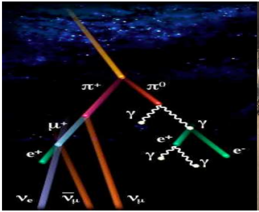
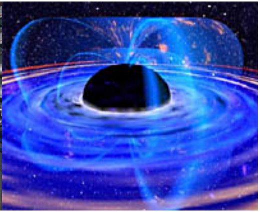


Sources of Neutrinos

Big Bang	Reactors	Sun	SuperNova
			
10^{-4} eV	few MeV	0.1-14 MeV	$\sim$ 10 MeV
$300/\mathrm{cm}^3$	$10^{21}/\mathrm{GW}_{th}/\mathrm{s}$	$10^{10}/\mathrm{cm}^2/\mathrm{s}$	$10^9/\mathrm{cm}^2/\mathrm{s}$

Atmosphere	Accelerators	Extragalactic
		
$\sim$ 1 GeV	1-20 GeV	TeV-PeV
few/cm^2/s	$10^5/\mathrm{cm}^2/\mathrm{s}$ (at 1km)	varies

Neutrinos and Todays Universe

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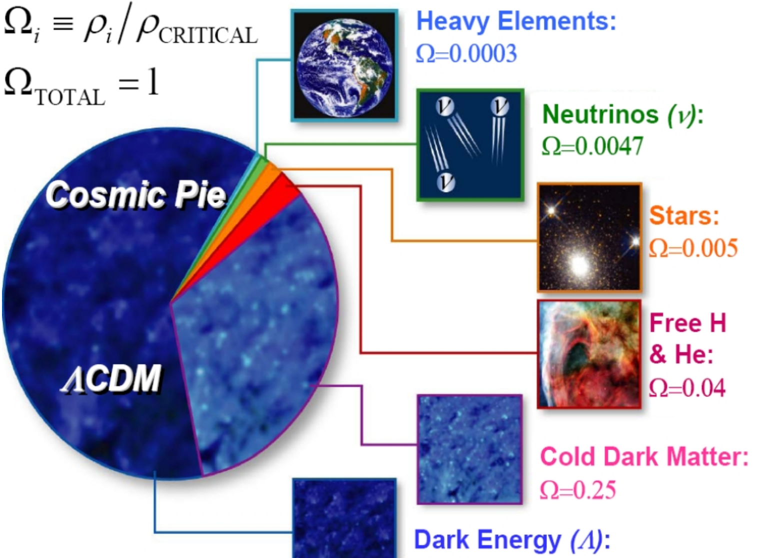
Neutrino mass $<$ 2 eV (beta-decay limits)



NEUTRINO MIXING AND OSCILLATIONS

Solar Neutrinos

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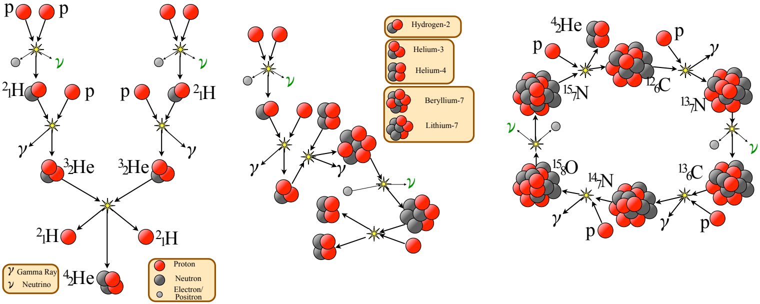
Fusion of nuclei in the Sun produces solar energy and neutrinos

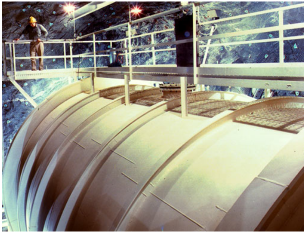


The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

1. $\nu_e^{sun} +^{37} CL \rightarrow e^- +^{37} Ar, \ \tau(^{37}Ar) = 35$ **days.**
2. **Number of** Ar **atoms** $\approx$ **number of** ν_e^{sun} **interactions.**

Ray Davis



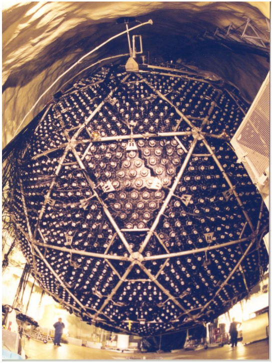
Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Where did the suns ν_e's go?

RAY DAVIS SHARES 2002 NOBEL PRIZE

SNO Experiment: Solar ν Measurments
$1 \leftrightarrow 2$ mix ing

2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water (0.5 B$ worth on loan from Atomic Energy of Canada Ltd.) located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following ν^{sun} interactions:



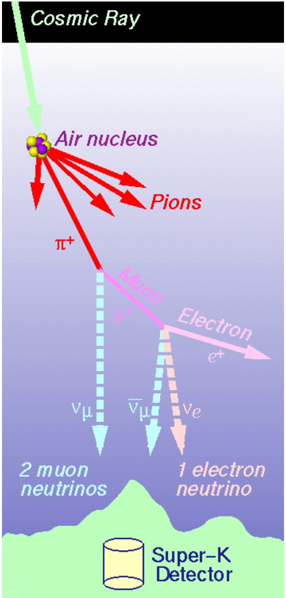
$$1)\ \nu_e + d \rightarrow e^- + p + p\ \text{(CC)}.$$
$$2)\ \nu_x + d \rightarrow p + n + \nu_x\ \text{(NC)}.$$
$$3)\ \nu_x + e^- \rightarrow e^- + \nu_x\ \text{(ES)}.$$

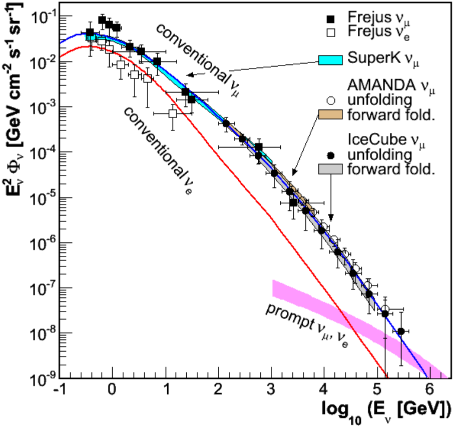
SNO measured:

$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6 cm^{-2}s^{-1}$$
$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\text{stat})^{+0.16}_{-0.14}(\text{sys.}) \pm \times 10^6 cm^{-2}s^{-1}$$
$$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\text{stat})^{+0.46}_{-0.43}(\text{sys.}) \pm \times 10^6 cm^{-2}s^{-1}$$

All the solar ν's are there but ν_e appears as ν_x!

Neutrinos from our Atmosphere: $\nu_\mu, \nu_e, \bar{\nu}$





Many decades in E

Neutrinos from our Atmosphere: $\nu_\mu, \nu_e, \bar{\nu}$

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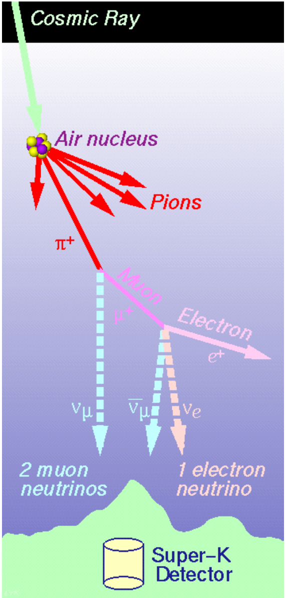
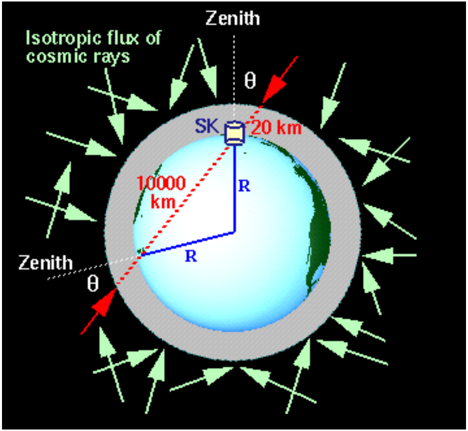
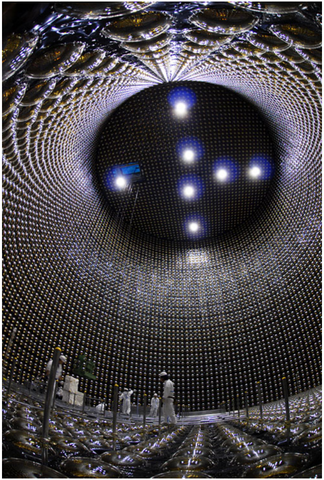


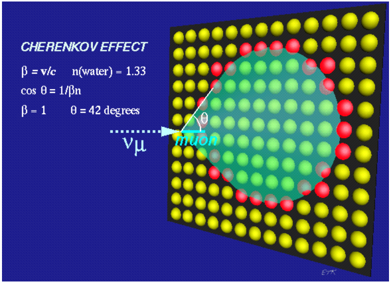


L = 0 to 13,000 km

The Super-Kamiokande Experiment. Kamioka Mine, Japan

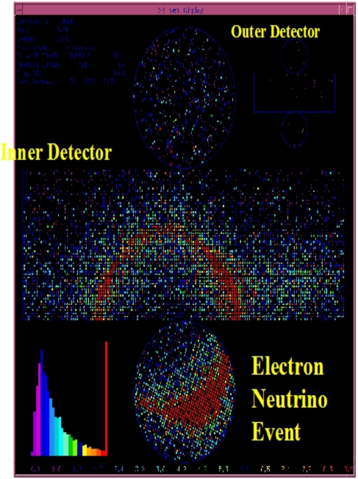


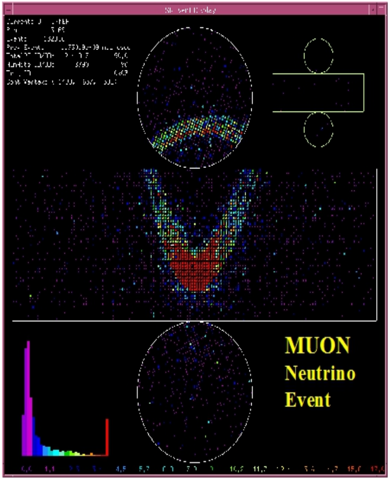
Neutrinos are identified by using CC interaction $\nu_{\mu,e} \rightarrow e^{\pm}, \mu^{\pm}X$. The lepton produces Cherenkov light as it goes through the detector:



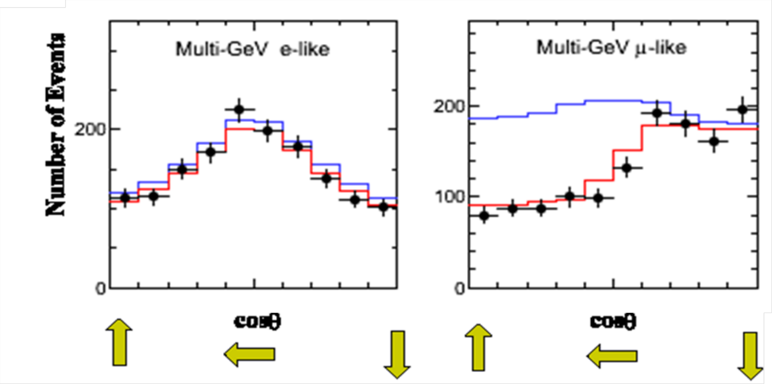
50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes.

The Super-Kamiokande Experiment. Kamioka Mine, Japan





More Disappearing Neutrinos!!



All the ν_e are there! But what happened to the ν_μ ??

Some Quantum Mechanics

1924: Louis-Victor-Pierre-Raymond, 7th duc de Broglie proposes in his doctoral thesis that all matter has wave-like and particle-like properties.

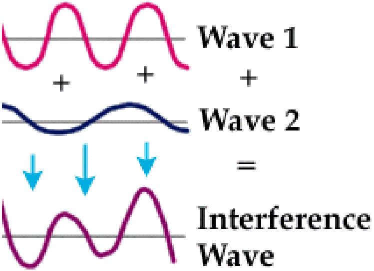
For highly relativistic particles : energy $\approx$ momentum

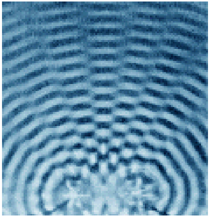
De Broglie

$$\text{Wavelength (nm)} \approx \frac{1.24 \times 10^{-6}\ \text{GeV.nm}}{\text{Energy (GeV)}}$$

Neutrino Mixing

1957,1967: B. Pontecorvo proposes that neutrinos of a particular flavor are a mix of quantum states with different masses that propagate with different phases:





The interference of water waves coming from two sources.

The inteference pattern depends on the difference in masses

Neutrino Mixing ⇒ Oscillations

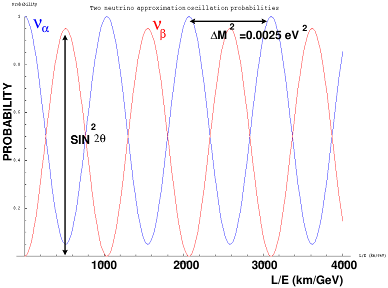
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

where $\Delta m^2_{21} = (m_2^2 - m_1^2)$ in eV^2, L (km) and E (GeV).

Observation of oscillations implies non-zero mass eigenstates



Two Different Mass Scales!

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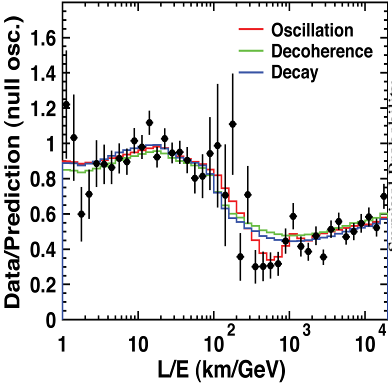
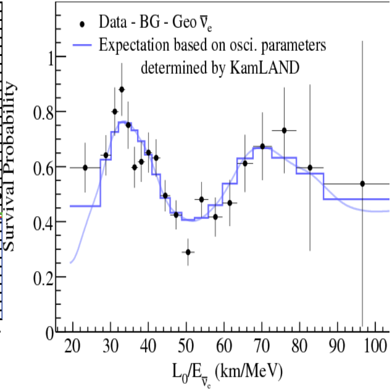
Super-K, atmospheric ν_μ



KamLAND, reactor $\bar{\nu}_e$



Global fit 2013:

$$\Delta m^2_{\rm atm} = 2.43^{+0.06}_{-0.10} \times 10^{-3}\ {\rm eV}^2$$
$$\sin^2\theta_{\rm atm} = 0.386^{+0.24}_{-0.21}$$

Atmospheric L/E $\sim$ 500 km/GeV

Global fit 2013:

$$\Delta m^2_{\rm solar} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ {\rm eV}^2$$
$$\sin^2\theta_{\rm solar} = 0.307^{+0.18}_{-0.16}$$

Solar L/E $\sim$ 15,000 km/GeV

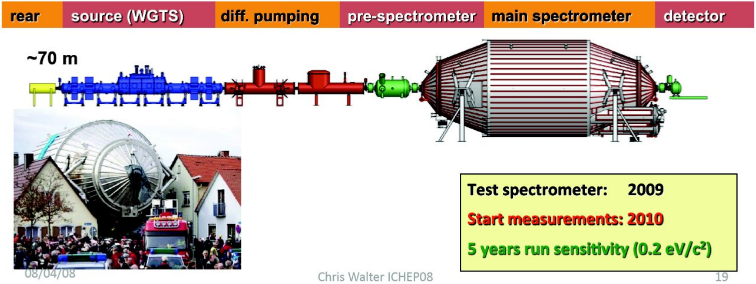
2015 Nobel Prize

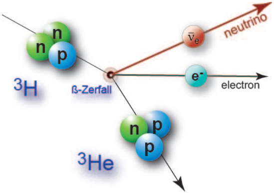
Takaaki Kajita
University of Tokyo, Japan
(SuperKamiokande)

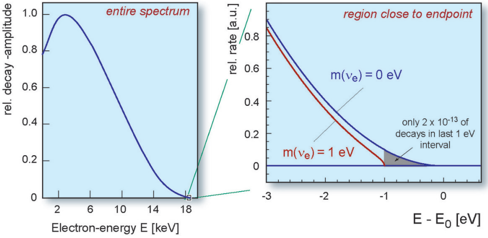
Arthur B. MacDonald
Queens University, Canada
(SNO)

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

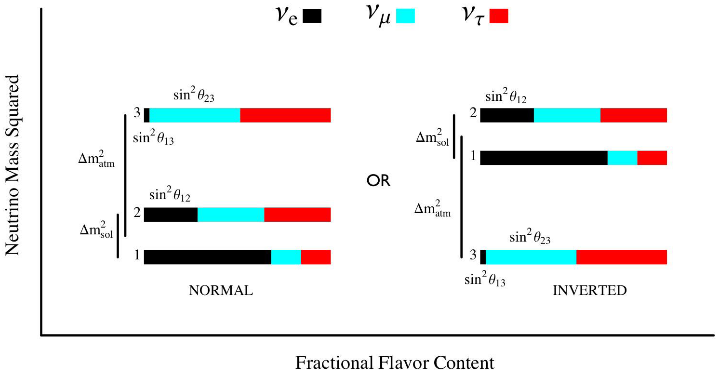
Measurement of the Absolute Neutrino Mass





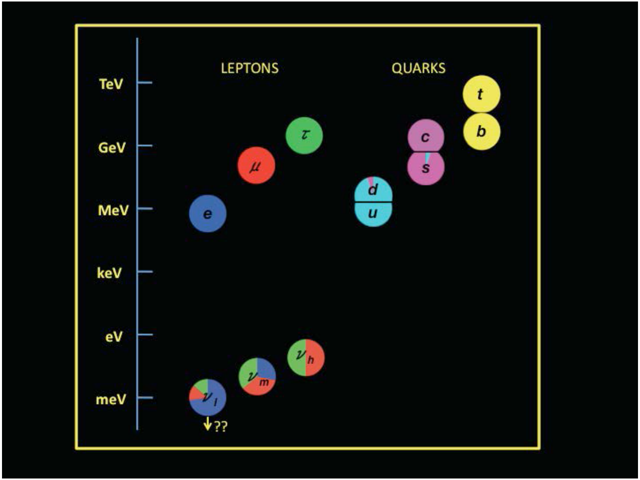


Neutrino Mixing: 3 flavors, 3 amplitudes, 2 mass scales



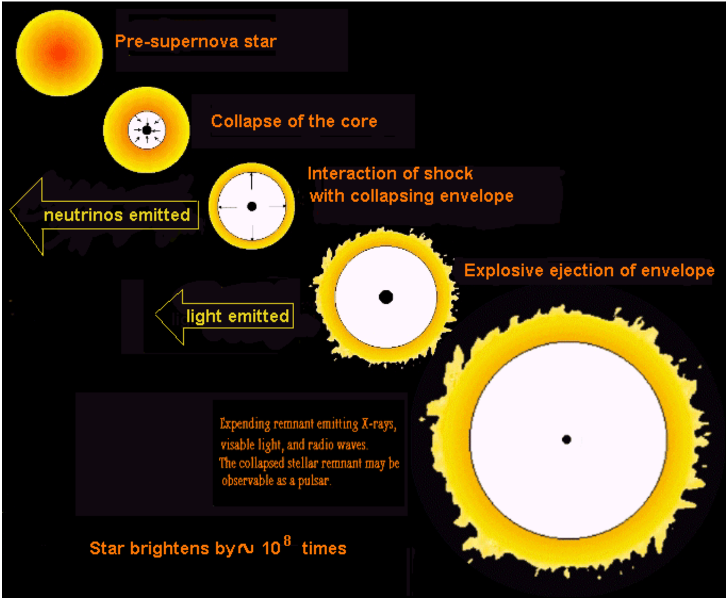
$$\sin^2\theta_{12} \approx \sin^2\theta_{\text{solar}}$$
$$\sin^2\theta_{23} \approx \sin^2\theta_{\text{atmospheric}}$$

Neutrino Mass Mysteries



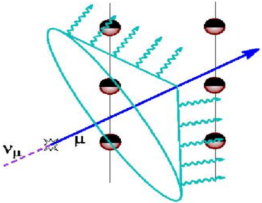
Why are neutrino masses so small??

Supernova Neutrinos

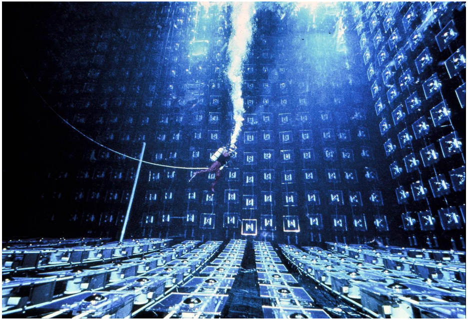


The Irvine-Michigan-Brookhaven (IMB) Detector

A relativistic charged particle going through water, produces a ring of light

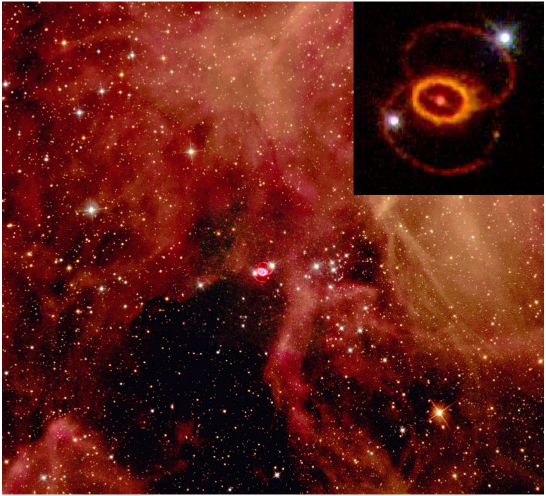


The Irvine-Michigan-Brookhaven Detector



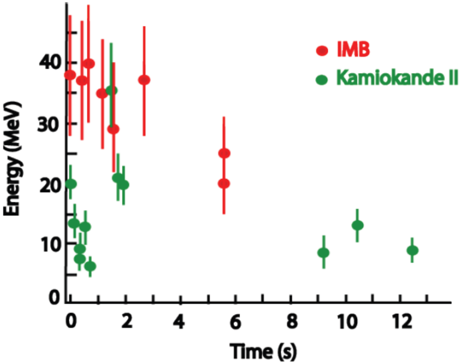
IMB consisted of a roughly cubical tank about 17 17.5 23 meters, filled with 2.5 million gallons of ultrapure water in Morton Salt Fariport Mine, Ohio. Tank surrounded by 2,048 photomultiplier tubes. IMB detected fast moving particles produced by proton decay or neutrino interactions

IMB/Kamioka Detect First Supernova Neutrinos!



1987: Supernova in large Magellanic Cloud (168,000 light years)

IMB/Kamioka Detect First Supernova Neutrinos!

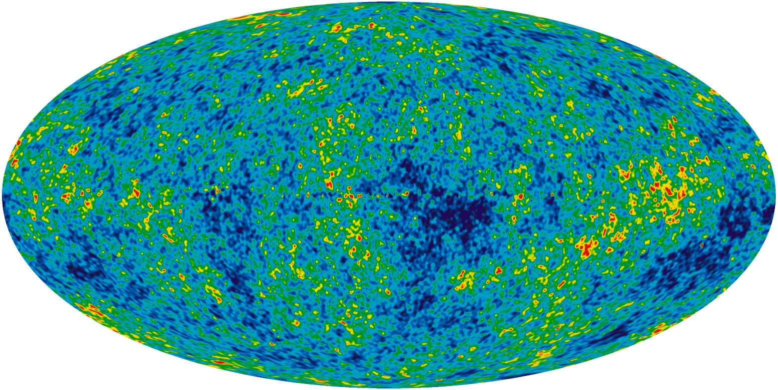


2-3 hrs earlier: IMB detects 8 neutrinos

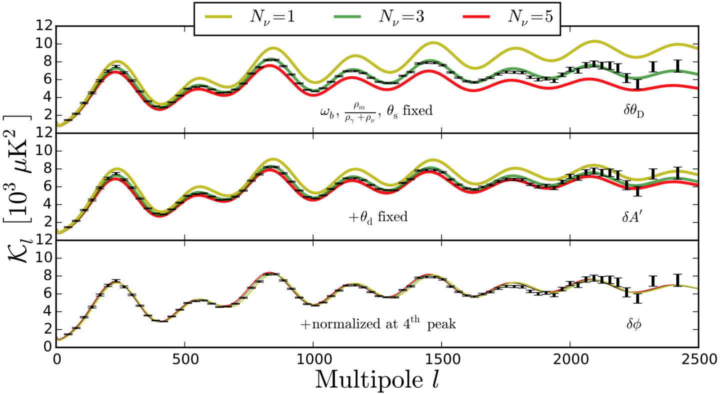
AND Kamioka detector (Japan) detects 11 neutrinos

Masatoshi Koshiba (Kamiokande, SuperKamiokande) shares 2002 Nobel Prize with Ray Davis for detection of Cosmic Neutrinos

The Cosmic Microwave Background



Big Bang Neutrinos and the CMB

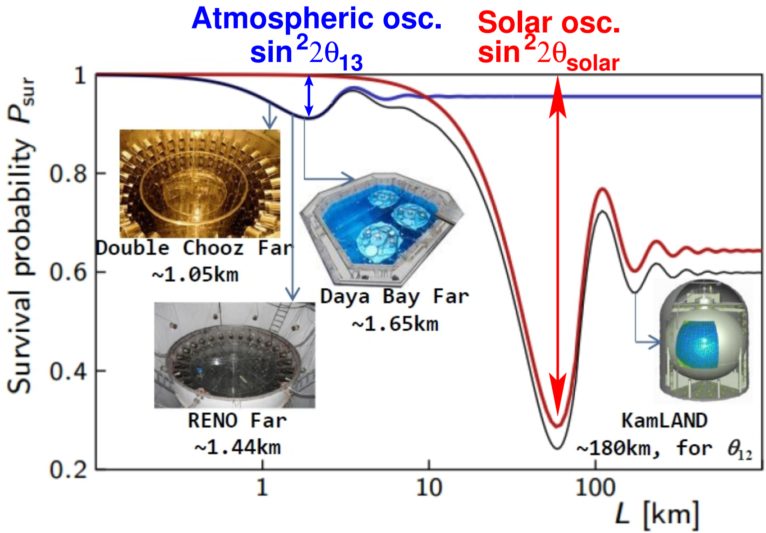


Current Neutrino Experiments

- MeV scale Neutrinos: The Daya Bay Reactor Experiment
- GeV scale Neutrinos: The T2K and NOνA experiments
- TeV-PeV scale Neutrinos: The IceCUBE Experiment

More Reactor $\bar{\nu}_e$: The 3rd Mixing Amplitude (θ_{13})

$\sin^2\theta_{13}$ = fraction of ν_e in ν_3 state, $\sin^2\theta_{12}$ = fraction of ν_e in ν_2 state



The Daya Bay Reactor Complex

Reactor Specs:

Located 55km north-east of Hong Kong.

Current: 2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 GW_{th}

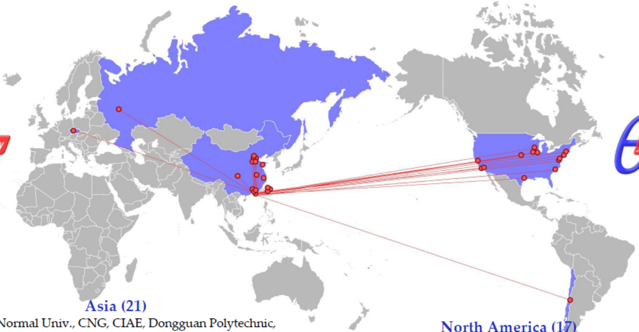
By 2011: 2 more cores at Ling Ao II site = 17.4 GW_{th} $\Rightarrow$ top five worldwide

$1\ GW_{th} = 2 \times 10^{20} \bar{\nu}_e/\text{second}$

Deploy multiple near and far detectors

Reactor power uncertainties $< 0.1\%$

The Daya Bay Collaboration : 231 Collaborators



Asia (21)

Beijing Normal Univ., CNG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (17)

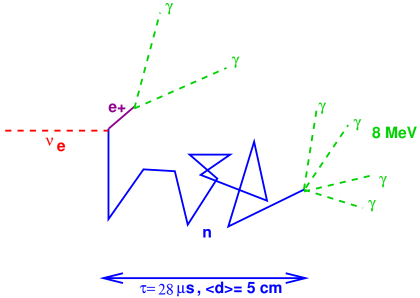
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic Univ. of Chile

Detecting Neutrinos from the Daya Bay Reactors

The active target in each detector is liquid scintillator loaded with 0.1% Gd

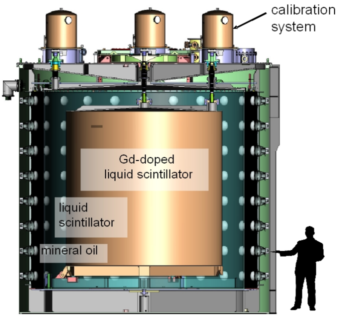


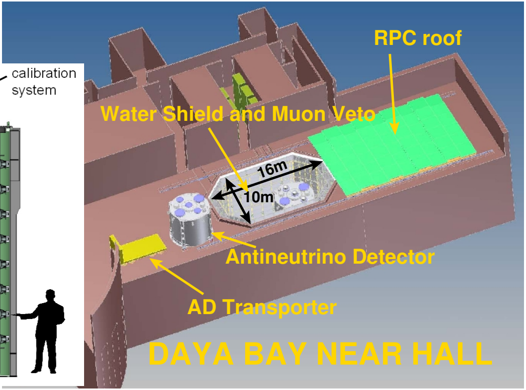
- $\bar{\nu}_e + p \rightarrow n + e^+$
- $e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV $+T_{e^+}$, prompt)
- $n + p \rightarrow D + \gamma$ (2.2 MeV, $\tau \sim 180\mu s$). OR
- $n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$'s (8 MeV, $\tau \sim 28\mu s$).

$\Rightarrow$ delayed co-incidence of e^+ conversion and n-capture ($>$ 6 MeV)

with a specfic energy signature

The Daya Bay Experimental Apparatus

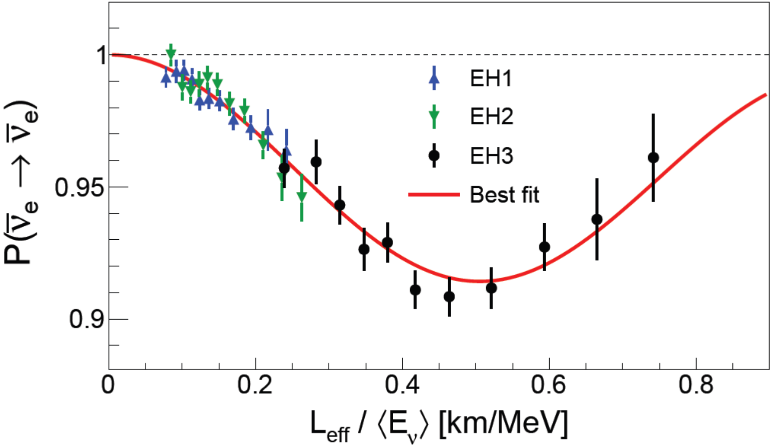




- Multiple "identical" detectors at each site.
- Manual and multiple automated calibration systems per detector.
- Thick water shield to reduce cosmogenic and radiation bkgds.

	DYB	LA	Far
Event rates/20T/day	840	740	90

Daya Bay Measurement of Non-zero θ_{13}

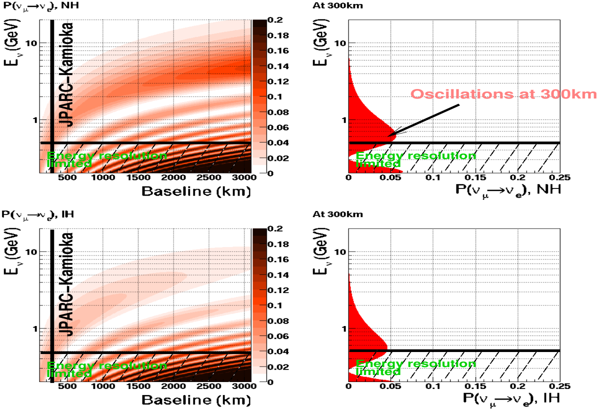


First to discover non-zero θ_{13} (2012) and currently most precise result:

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

Matter Effect on Neutrino Oscillation

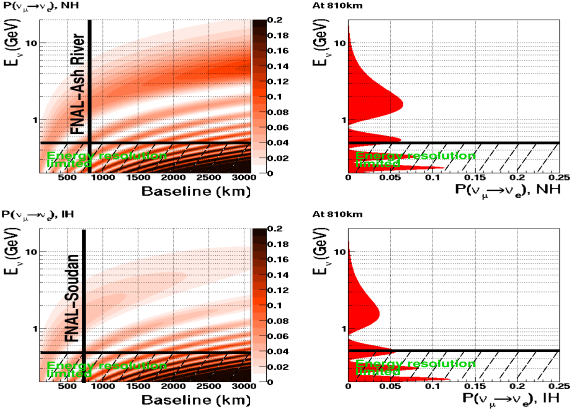
1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter acts as a refrective index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.



We can determine the mass ordering - $m_3 > m_1$ (NH) or $m_1 > m_3$ (IH) - of neutrinos using $\nu_\mu \to \nu_e$ oscillations over long distances.

Matter Effect on Neutrino Oscillation

1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter acts as a refrective index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.



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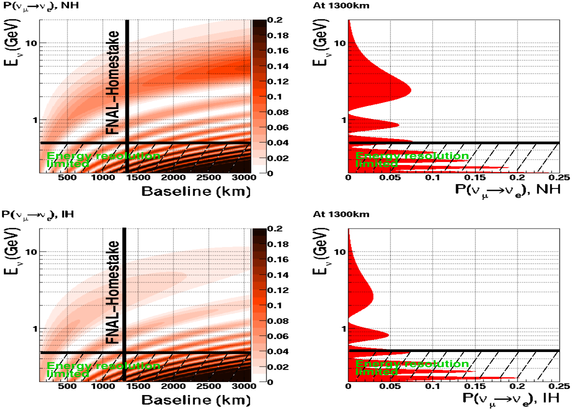
Matter Effect on Neutrino Oscillation

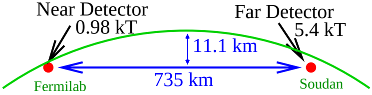
1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter acts as a refrective index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.



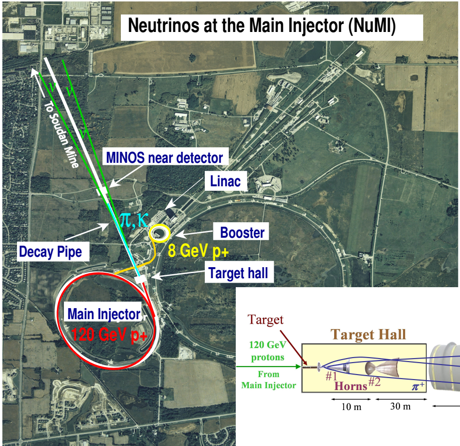
We can determine the mass ordering - $m_3 > m_1$ (NH) or $m_1 > m_3$ (IH) - of neutrinos using $\nu_\mu \rightarrow \nu_e$ oscillations over long distances.

Neutrinos at the Main Injector

The longest baseline accel. ν expt in operation. Average power = 500 kW. Upgrade to 700kW in 2016

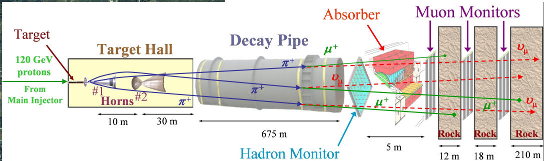


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**



NuMI Horn 2 inner conductor
Radial field, $B \propto 1/r$

3T at 200 kA



Making Neutrinos and Anti-Neutrinos

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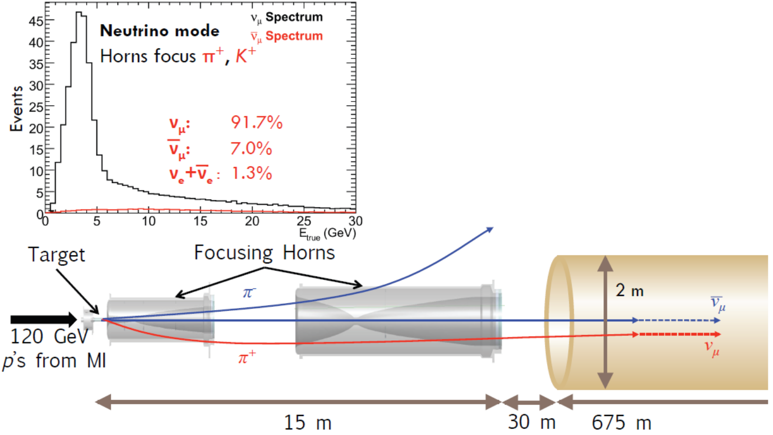
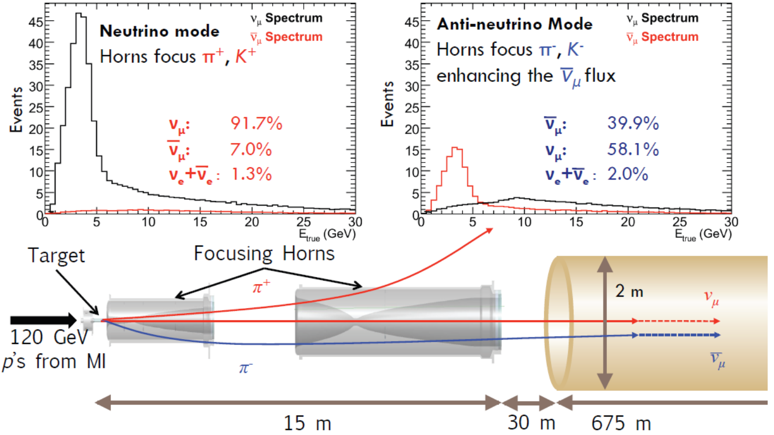


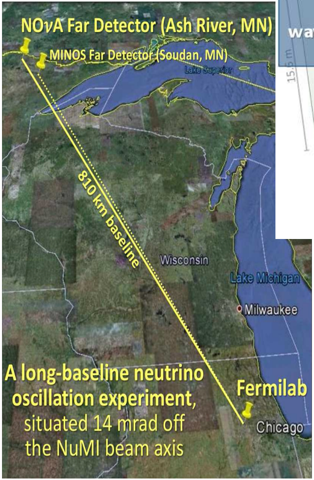
P. Vahle, Neutrino 2010

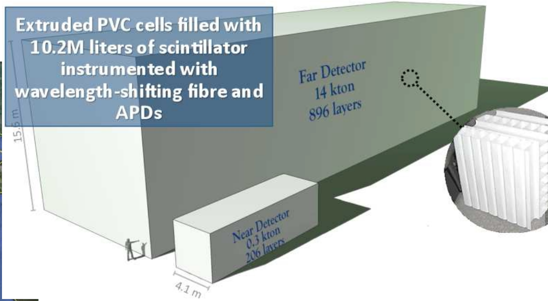
Making Neutrinos and Anti-Neutrinos

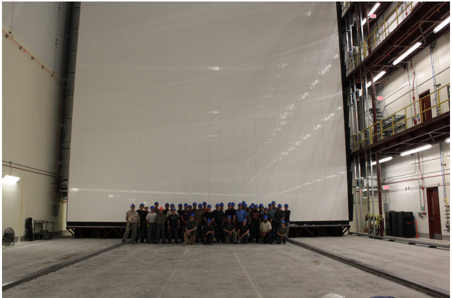


P. Vahle, Neutrino 2010

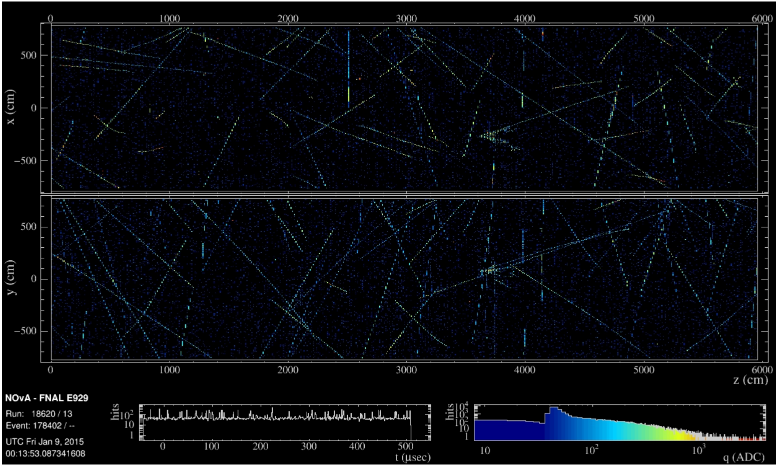
The NOνA Experiment



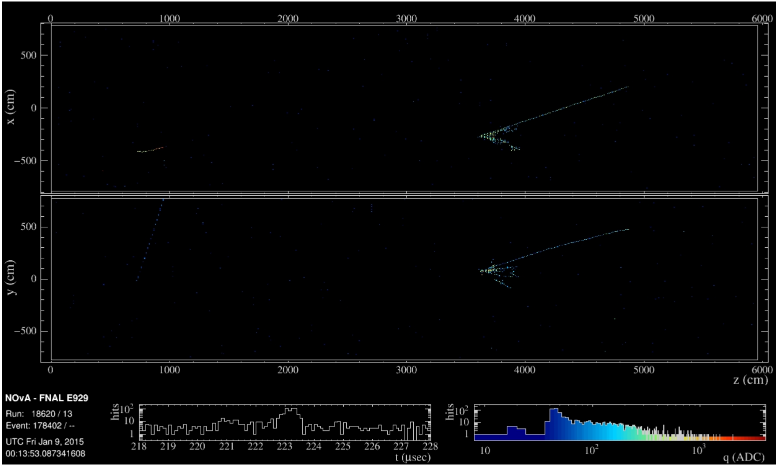




NOνA Collecting Neutrino Events

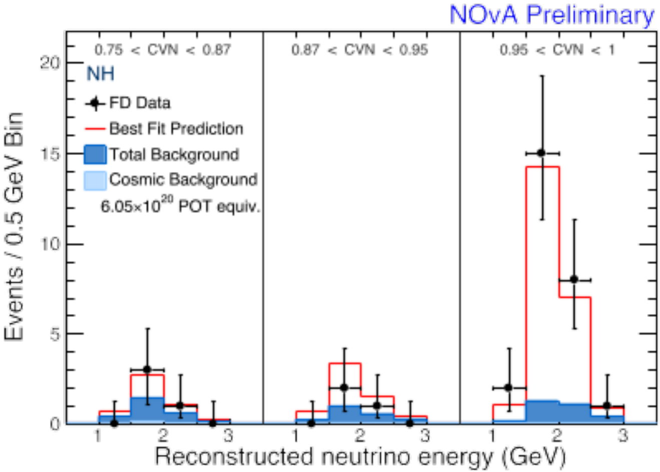


NOνA Collecting Neutrino Events



NOνA Results 2016

A total of 33 $\nu_\mu \rightarrow \nu_e$ candidate events

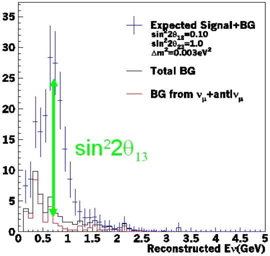


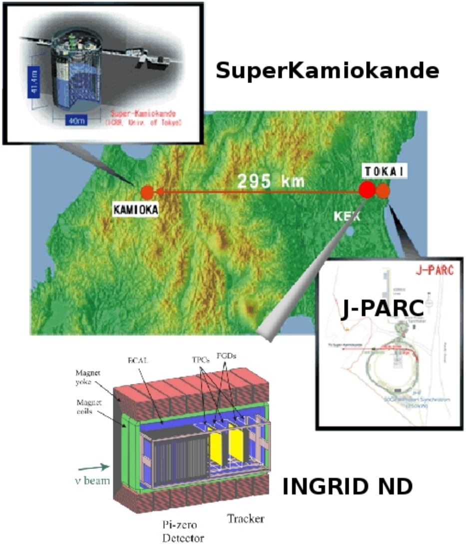
Some indication of normal mass hierarchy when combined with T2K

Off-axis high intensity accelerator ν_μ beams: T2K

First proposed for BNL E-889 (1995): A narrow beam of ν can be achieved by going off-axis to the π beam. Better S:B at oscillation max.

$\nu_\mu \to \nu_e$ Appearance Signal:





T2K first results announced in March 2011

T2K beam ν_e Candidate Event 2010

The Little Neutral One

Mary Bishai
Brookhaven National Laboratory

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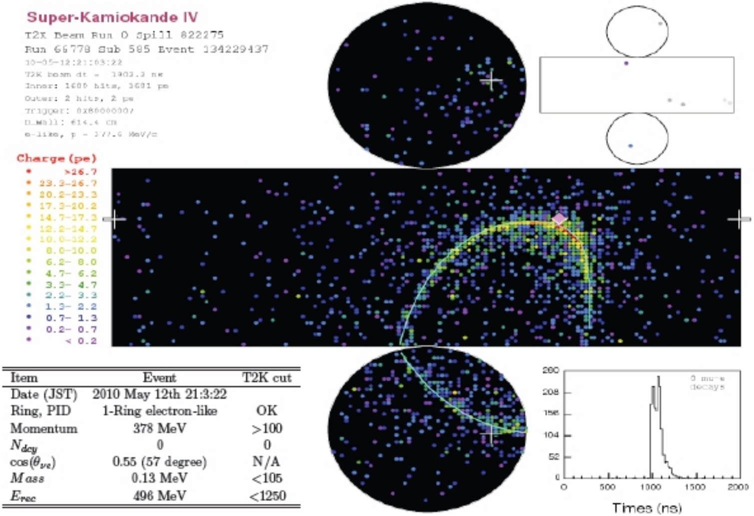
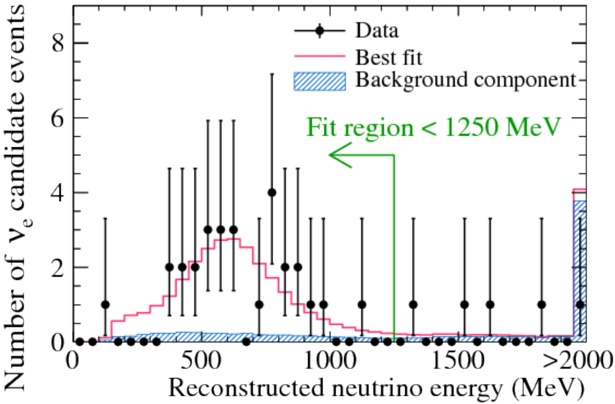


Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

T2K: First Observation of $\nu_\mu \rightarrow \nu_e$ APPEARANCE



In 2014 T2K observes conversion of ν_μ to ν_e (atmospheric oscillation scale) with an amplitude of $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$.

2016 Breakthrough Prize in Fundamental Physics

The Little Neutral One

Mary Bishai
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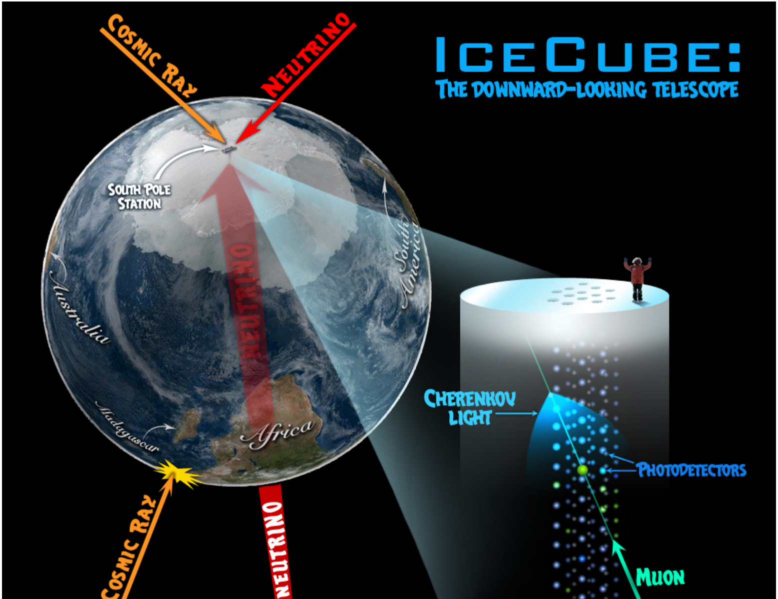
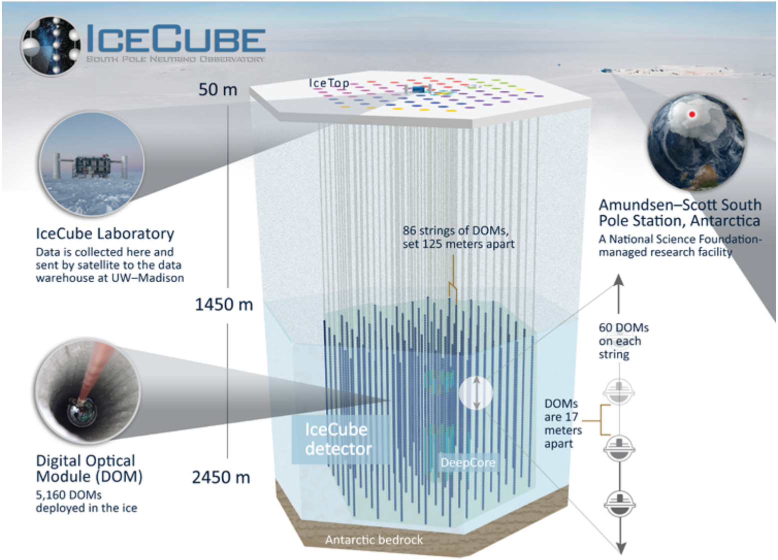
The 2016 Breakthrough Prize in Fundamental Physics awarded to 7 leaders and 1370 members of 5 experiments investigating neutrino oscillation: Daya Bay (China); KamLAND (Japan); K2K / T2K (Japan); Sudbury Neutrino Observatory (Canada); and Super-Kamiokande (Japan)

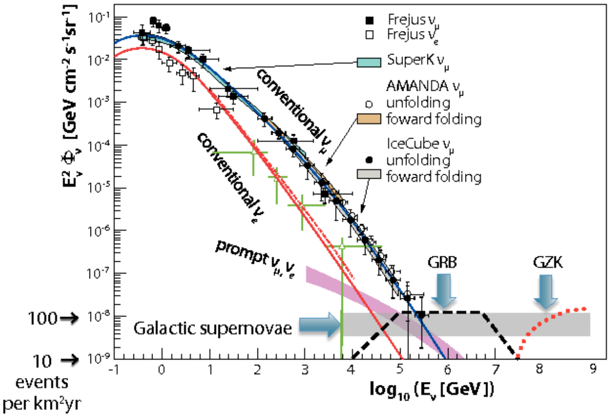
The IceCUBE Experiment



The IceCUBE Experiment

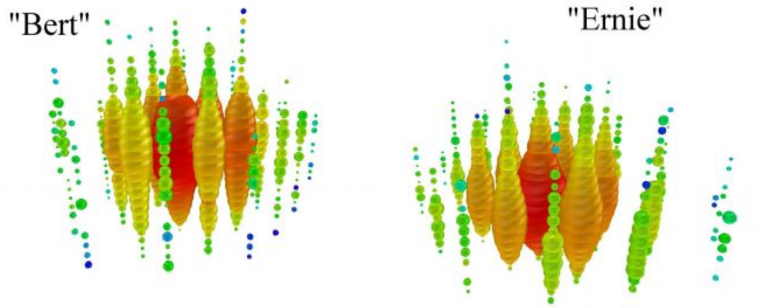


The Highest Energy Neutrinos (Gamma Ray Bursts)

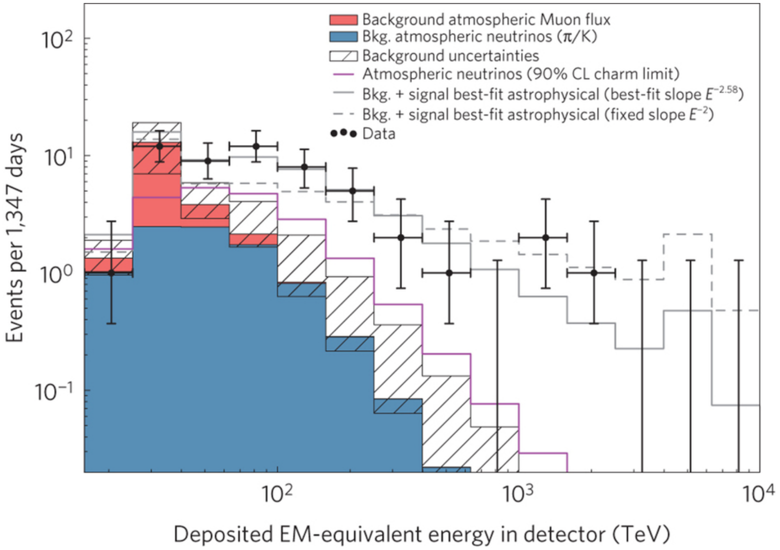


The Highest Energy Neutrinos (Gamma Ray Bursts)

Neutrino events with energies > PeV ($10^{15}eV$)



The Highest Energy Neutrinos (Gamma Ray Bursts)



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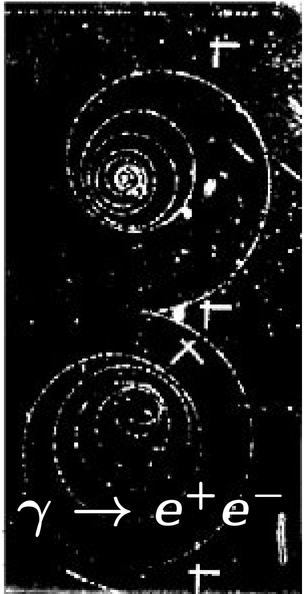
Charge-Parity Symmetry

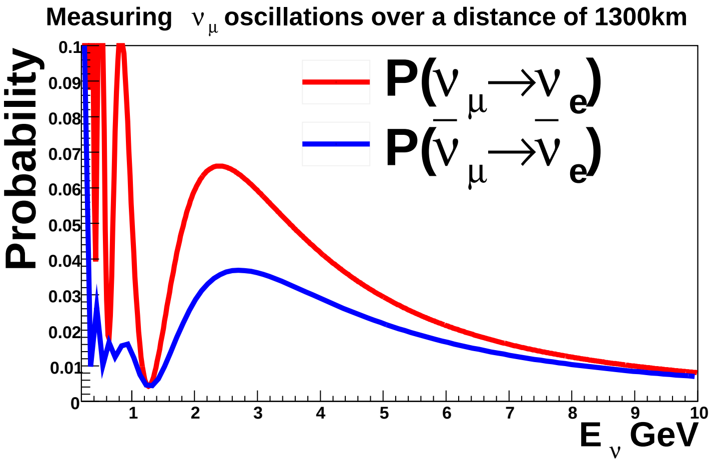
Charge-parity symmetry: laws of physics are the same if a particle is interchanged with its anti-particle and left and right are swapped.

A violation of CP $\Rightarrow$ matter/anti-matter asymmetry.



Charge-parity Symmetry and Neutrino Mixing

Could neutrinos and anti-neutrinos oscillate differently?



Could this explain the excess of matter in the Universe?

The Deep Underground Neutrino Experiment

The Little Neutral One
Mary Bishai Brookhaven National Laboratory
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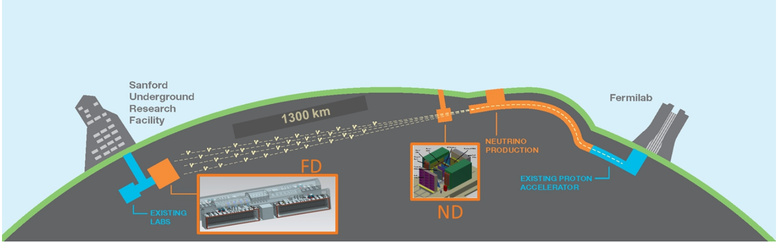
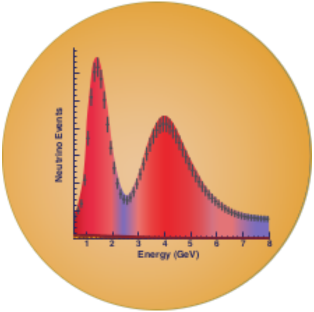


- **A very long baseline experiment:** **1300km from Fermilab in Batavia, IL to the Sanford Underground Research Facility (former Homestake Mine) in Lead, SD.**
- **A highly capable near detector at Fermilab.**
- **A very deep (1 mile underground) far detector: massive 40-kton Liquid Argon Time-Projection-Chamber with state-of-the-art instrumentation.**
- **High intensity *tunable* wide-band neutrino beam from LBNF produced from upgraded MW-class proton accelerator at Fermilab.**

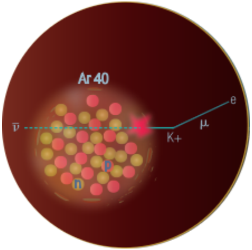
The DUNE Scientific Collaboration

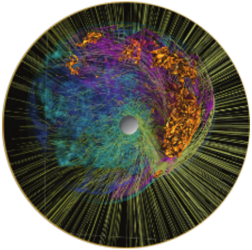
Scientific Objectives of DUNE



1. **precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ oscillations; this includes precision measurement of the third mixing angle θ_{13}, measurement of the charge-parity (CP) violating phase $\delta_{\rm CP}$, and determination of the neutrino mass ordering (the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$), the so-called mass hierarchy**
2. **precision measurements of the mixing angle θ_{23}, including the determination of the octant in which this angle lies, and the value of the mass difference, —Δm^2_{32}—, in $\nu_\mu \to \nu_{e,\mu}$ oscillations**

Scientific Objectives of DUNE

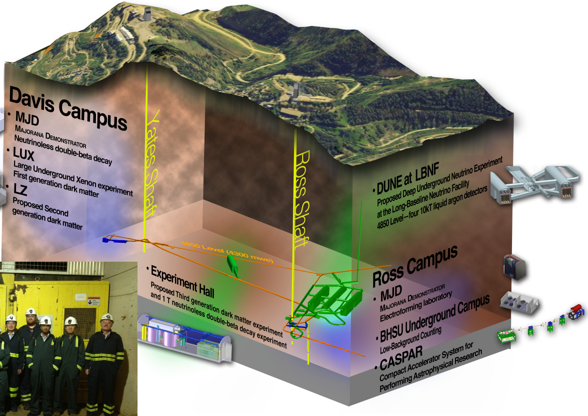




3. search for proton decay, yielding significant improvement in the current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g., $p \rightarrow K^{+}\overline{\nu}$

4. detection and measurement of the neutrino flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of DUNE

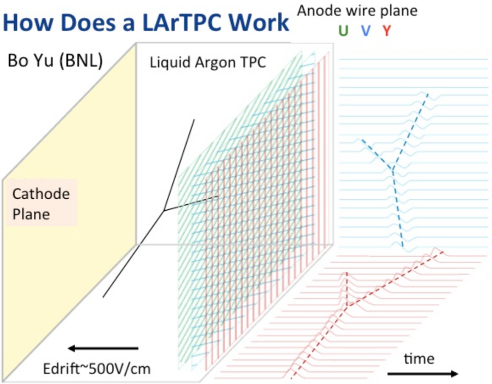
The Sanford Underground Research Facility



Experimental facility operated by the state of South Dakota. LUX (dark matter) and Majorana ($0\nu - 2\beta$) demonstrator operational expts at 4850-ft level. Chosen as site of G2 dark matter experiment

The DUNE Far Detector

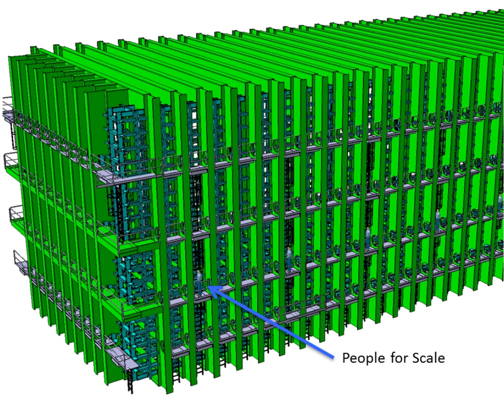
A large cryogenic liquid Argon detector located a mile underground in the former Homestake Mine with a mass of at least 40 kilo-tons is used to image neutrino interactions with unprecedented precision:

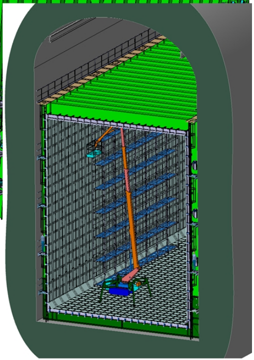


The wireplane in a small LArTPC

The DUNE Far Detector

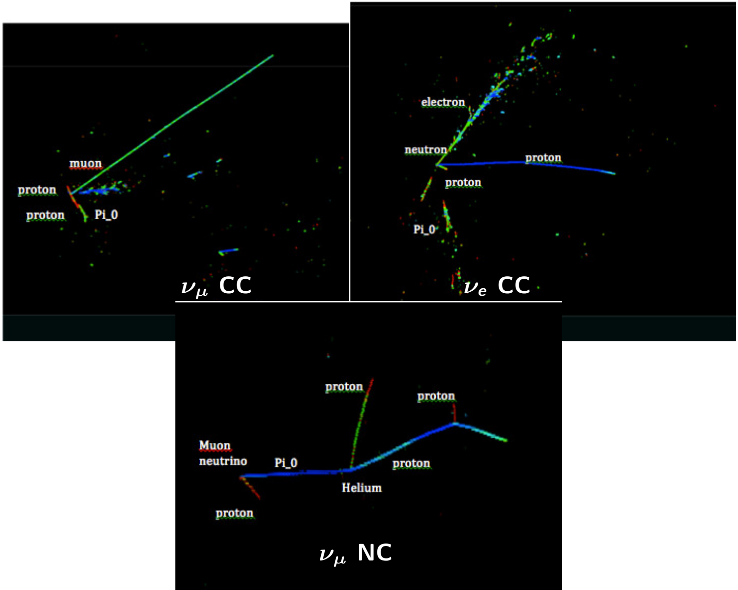
The 40-kton (fiducial) detector is constructed of four modules with a total mass of 17.4 kton each.





<u>External (Internal) Dimensions</u>
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L

Reconstructed Neutrino Interactions in a LArTPC



Oscillation signals Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$)

The Little Neutral One
Mary Bishai Brookhaven National Laboratory
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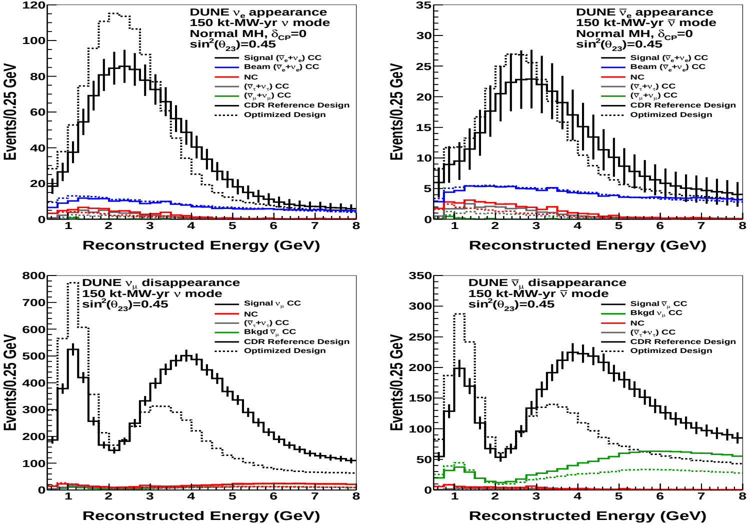

Simultaneous fit to all four samples to determine osc. params

Possible Supernova Signature in DUNE

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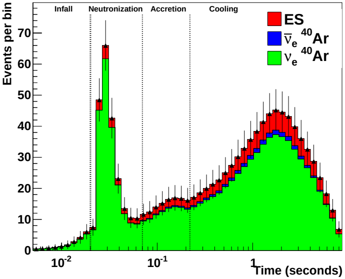
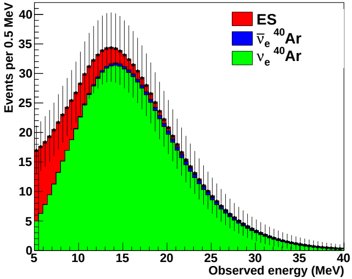
Liquid argon is particularly sensitive to the ν_e component of a supernova neutrino burst:

$$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*, \tag{1}$$

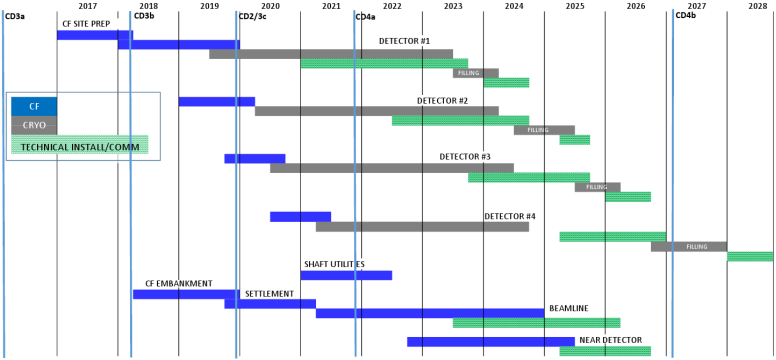
Expected time-dependent signal in 40 kton of liquid argon for a Supernova at 10 kpc:





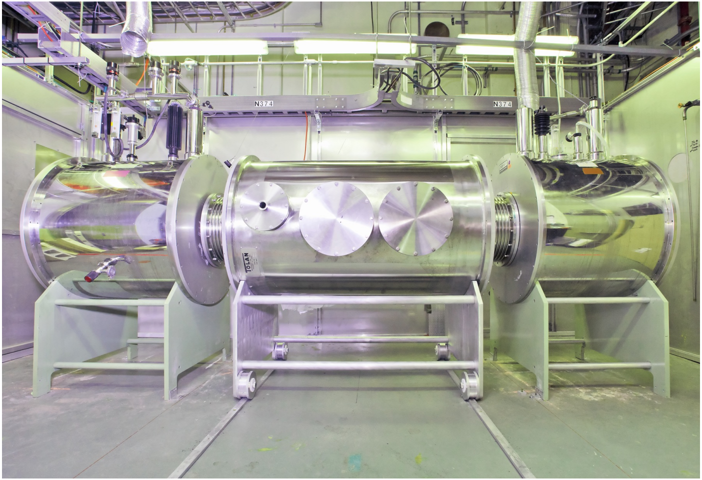
Time distribution **Energy spectrum (time integrated)**

LBNF/DUNE Schedule



PTOLEMY: Detecting Big Bang Neutrinos

Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield



How to detect Big Bang Neutrinos

From paper by Steven Weinberg in 1962 (Phys. Rev. 128:3 1457]. Detect capture of BB neutrinos on a beta decaying nucleus:

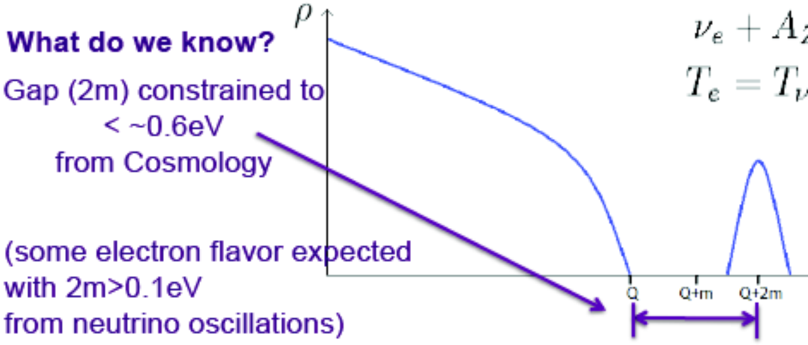
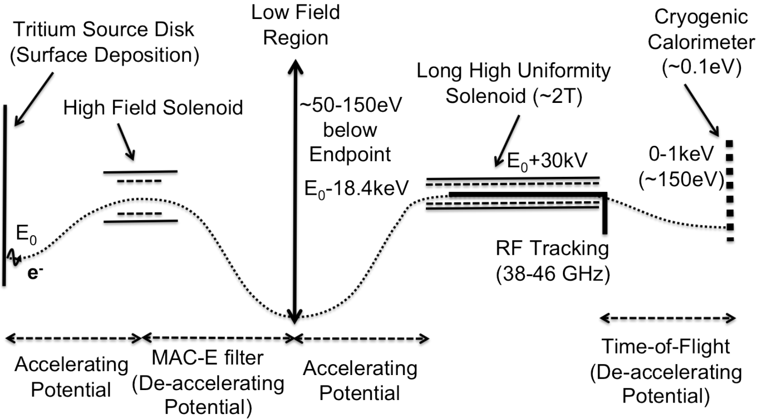


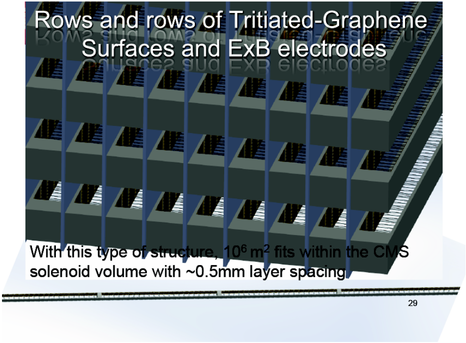
Figure 1: Emitted electron density of states vs kin
capture on beta decaying nuclei. The spike at $Q +$

Experimental Concept

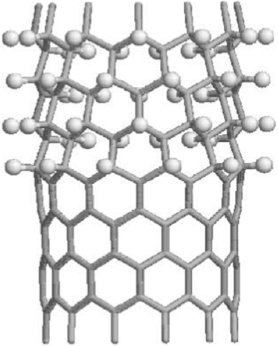


Many techincal challenges!!!

The biggest nearly insurmountable problem for relic neutrino detection using capture on tritium is to provide a large enough surface area to hold at least 100 grams of weakly bound atomic tritium!



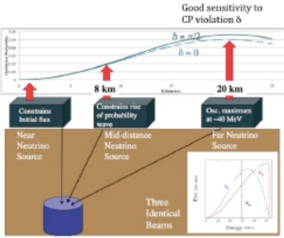
Ultra-modern materials science needed: Use tritium trapped in very thin layers of graphene:



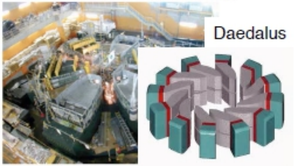
Practical Applications of Technologies for ν Experiments

Synergies and Applications - Examples

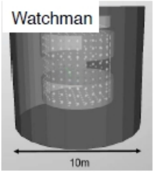
Cyclotrons for neutrino physics
(and industrial applications)



RIKEN K2600 SUPERCONDUCTING RING CYCLOTRON



Neutrino detectors for reactor monitoring and non-proliferation



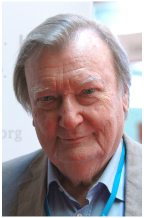
remote discovery of undeclared nuclear reactors with large detectors at km scale

US Short-Baseline Experiment

reactor antineutrino studies at short baselines

Multi-MW Accelerators Driving Thorium Reactors

First proposed by Carlo Rubbia in 1995 (1984 Nobel Prize winner)



Global energy resources in ZetaJoules

Resource	Type	Yearly consumption (1999) ZJ	Resources ZJ	Consumed until 1999 (ZJ)
Oil	Conventional	0.13	12.08	4.85
	Unconventional	0.01	20.35	0.29
	Total oil	0.14	32.42	5.14
Natural gas	Conventional	0.08	16.56	2.35
	Unconventional	0.00	33.23	0.03
	Total gas	0.08	49.79	2.38
Coal	Total coal	0.09	199.67	5.99
Total Fossils		0.31	281.88	13.51
Uranium	Thermal reactors	0.04	5.41 (2'000, sw)	
	Breeder	0	324 (120'000, sw)	
Thorium			1'300'000	

sw: including sea water
1 ZJ (ZetaJoule)= 10^3 EJ(ExaJoule)= 10^{21} J(Joule)

Requires proton accelerators with powers of 10 MW. Currently neutrino and neutron experiments are driving the technology of high power MW class proton beams.

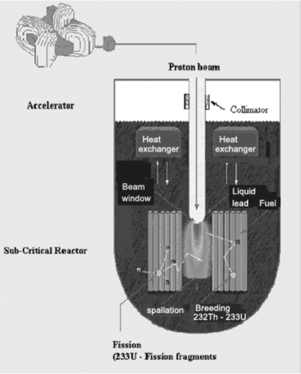


Figure 1. Schematic representation of Energy Amplifier proposed by Rubbia [4]

Neutrinos and Earth's Geology

The Little Neutral One

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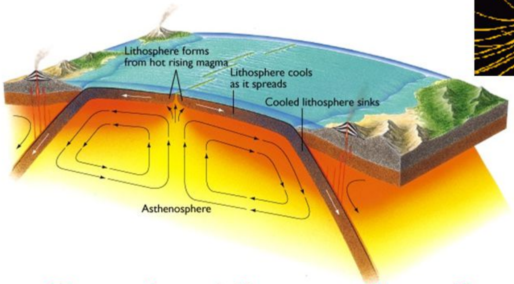
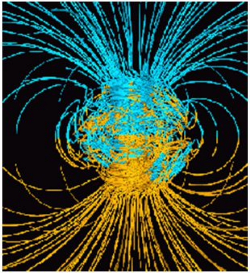
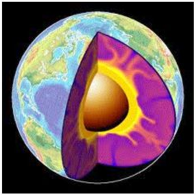
Plate Tectonics, Convection, Geodynamo



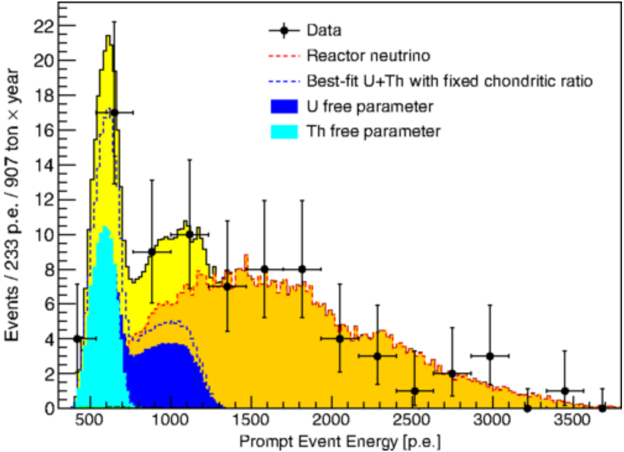




Does heat from radioactive decay drive the Earth's engine?

Neutrinos and Earth's Geology

Signal of $\bar{\nu_e}$ from radioactive decays of U/TH in the earth observed in the BOREXINO solar neutrino experiment:



Summary

- **Neutrinos have been at the forefront of fundamental discoveries in particle physics for decades.**
- **Discoveries of neutrino properties like the very small mass, large almost maximal mixing, are the** *ONLY direct evidence for physics beyond the Standard Model of particle physics, and new hidden symmetries.*
- **Neutrinos straddle the fields of nuclear physics, particle astrophysics, cosmology and high energy particle physics. Thus, they provide a unique probe to test for consistency in our picture of the Universe from the development of the Big Bang, the mechanics of Supernova explosions, the chemistry of stars, the geology of the earth, and the nuclear physics of reactors.**
- **Studying the properties of neutrinos with energies varying from the very cold (Big Bang ν) to the PeV scale requires a huge diversity of experiments, each with its own unique technical challenges.**

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